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Development of Electronic actuation system for Shape Memory Alloy based Aerospace Structures

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ABSTRACT

Shape memory alloy (SMA) is being widely used to implement smart concepts such as shape control and vibration suppression of aerospace structures. Shape memory alloy wires while undergoing phase transformation from martensite state to austenite state produce large strains. While doing so they serve as actuators and generate large forces when constrained while recovering their pre-defined shape, imparting this force to the structural component on which they are mounted which results in its movement. While designing the electronic system to energise an aerospace structure with shape memory alloy based actuators the amount of current and time for which this current is passed through the shape memory alloy wire are important considerations. It is equally important to design very efficient and miniature power sources (constant voltage as well as constant current) and control system to achieve fine and steady positioning of the structural component. This paper discusses different issues involved, as well as design and development of the electronics and control system for actuating and controlling a typical aerospace structural component with SMA actuators.

Key words: Shape Memory Alloy (SMA), Actuator, Power sources, Electronics, and Control system.

1. INTRODUCTION

Shape memory effect is based on a solid-solid phase transformation of the shape memory alloy that takes place with in a specific temperature (say from ambient to about 120^{o}C), which produces large strains. There are two states of Shape memory alloy namely martensite (cold shape) and austenite (hot shape). The properties of shape memory alloy vary with its temperature. Forward and reverse transformation occurs at different temperatures, resulting in hysteresis, which depends on the thermo-mechanical treatment as well as composition of shape memory alloy. Nickel-Titanium-Copper shape memory alloy commercially known as nitinol has best properties for actuator applications.

The required heat energy to shape memory alloy to undergo the phase transformation can be supplied either directly by passing electrical current or indirectly by placing the shape memory alloy wire in a controlled heating environment such as oven, immersing it in a hot liquid bath, winding coil around the shape memory alloy and passing current through this coil to heat the SMA wire, etc. However, for better control and also for making it amenable for interfacing with the computer, the preferred mode of heating the wire is by passing the electrical current directly through the wire.

The mechanical and electrical properties determine the behavior of shape memory alloy during phase transformation. So, the system design has to take care of these properties. Since the shape memory alloy shows hysteresis and decrease in resistance with increase in temperature in the forward phase transformation region, the system design should also cater to these requirements.

1.1 Shape control

Controlled shape change of an aerospace structural component is brought about in order to improve and optimise its aerodynamic efficiency under varying flight conditions. Shape memory alloy's in wire form can be effectively integrated into the structural component and energised to bring about the shape change.

1.2 Vibration suppression

Shape memory alloy's can be utilised to suppress steady state vibrations of a structural component. By energising shape memory alloy's integrated into a structural component the stiffness of the component changes there by shifting its natural frequency. By employing proper feed back one can also reduce the amplitude of steady state vibration at a particular natural frequency of the structure.

2. EXPERIMENTAL WORK

Figure 1 shows a set up to measure the resistance (in-turn the resistivity) of the shape memory alloy wire during its phase transformation, which is an important parameter in the design of power sources for actuation[1]. It can be explained in the following way:

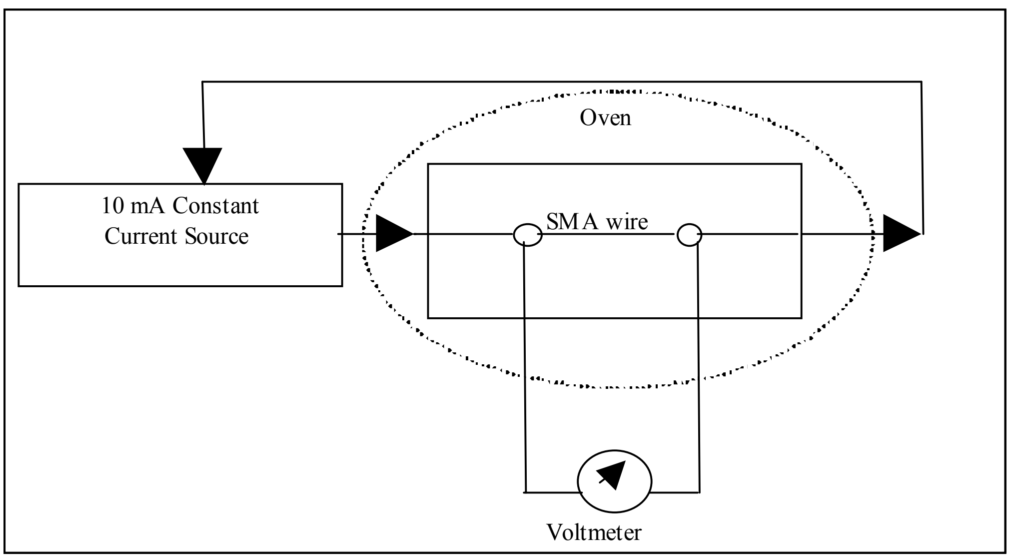


Figure 1. Schematic of experimental set up for resistance and resistivity measurement of SMA wire

A constant current source was designed, to drive about 10mA through the shape memory alloy actuator wire mounted inside an oven. This is taken as the reference current (I). However, this current is negligible compared to the current required (about 1200mA to 1550mA) to directly heat the shape memory alloy wire to take it through its phase transformation from martensite to austenite. In this experiment, the phase transformation is brought about by externally heating the shape memory alloy wire mounted inside the oven from room temperature (30^{o}C) to about 110^{o}C, by changing the oven temperature. At different oven temperature the voltage (V) across the shape memory alloy wire is measured while maintaining a constant current of 10mA through the wire. Then at selected oven temperature values the resistance(R) and in turn resistivity (ρ) value is calculated from the known relations.

$R=V/I$ and $\rho=R*(A/L)$

Where,

A – the area of the cross section of the shape memory alloy wire.

L – the length of the shape memory alloy wire.

During the experiment, the change in length (Strain) and temperature of the shape memory alloy wire is acquired using a Data Acquisition System (DAS) developed for this purpose. The output from the LVDT, which measures the strain, and the Thermocouple, which measures the temperature were suitably signal conditioned before feeding to the DAS. The thermocouple signal conditioner was designed using an analog devices IC – AD595 which is compact, versatile and includes feature such as cold junction compensation built into its design. The schematic in Figure 2 shows the DAS developed for generating the required strain Vs temperature plot. A 16-channel personal computer compatible data acquisition card was used to acquire strain and temperature data.

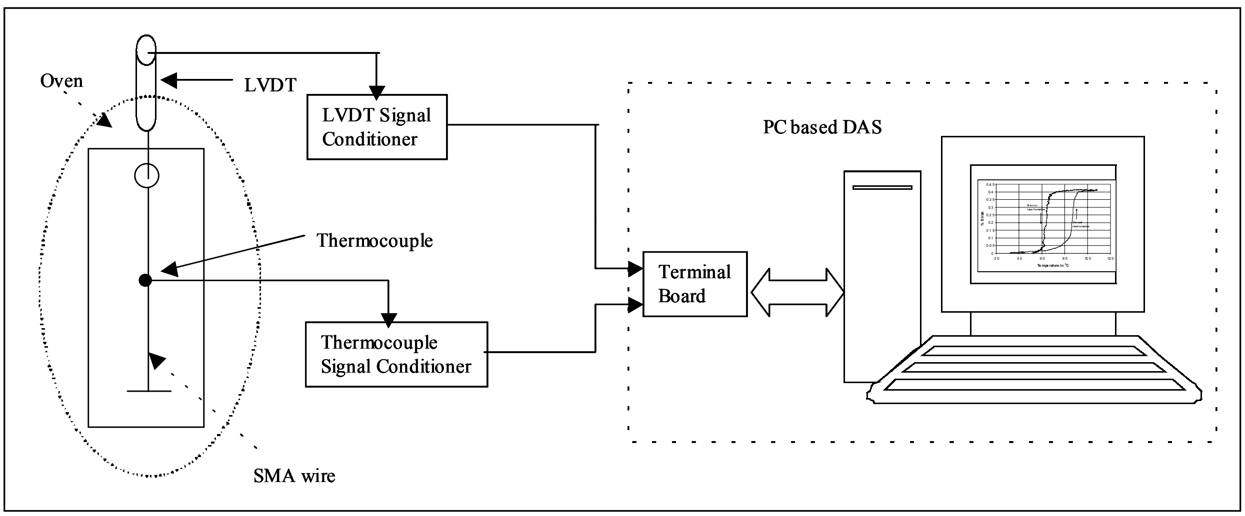


Figure 2. Data acquisition system for strain and temperature measurement

The software for acquiring the above data and plot the resulting hysteresis curve was developed using 'C' language. The acquired data is plotted in Figure 3. The plot shows hysteresis behaviour during heating & cooling, which is typical of a shape memory alloy wire[2]. This type of data generated about the SMA wire behaviour provides valuable information for design of power sources and feedback controller.

From some of the basic experiments carried out on shape memory alloy wire actuation by electrical method it has been observed that both the value of the current and the time of passage of current through the shape memory alloy wire are important parameters in any actuator application.

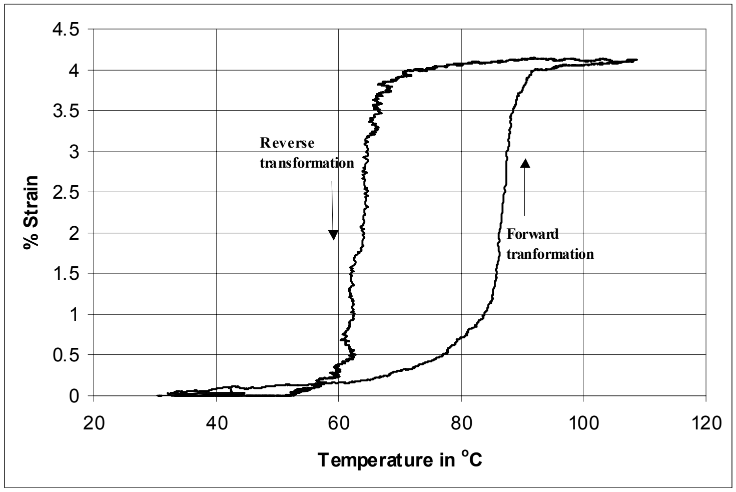


Figure 3. Plot of Temperature Vs Strain of a SMA wire

The phase transformation of the shape memory alloy wire is almost instantaneous due to passage of current resulting in large strain. This in turn produces an angular movement of the structural component on which the shape memory alloy wires are mounted. This angular movement is measured by a position sensor unit, which consists of a potentiometer mounted at the point of rotation on the structural component, there by providing input to the position controller.

3. DESIGN CRITERIA

The requirement of heating current of a shape memory alloy wire depends on its cross sectional area which in turn depends on its diameter i.e. on its current density. For the shape memory alloy wire chosen, the requirement of current varied from 1.2A to 1.55A and voltage around 5V. This called for designing and developing voltage and current sources. Both voltage and current sources have been designed and implemented. It has been found that constant current source is really advantageous when the shape memory alloy elements are remotely located from the source of power as in an aircraft environment. The power sources are made compatible to work from inputs such as 12V / 24V-28V available on the aircraft power bus. When individual miniature power sources and electrically isolated shape memory alloy actuator wires are employed, redundancy in the system is improved because the failure of the single source or single shape memory alloy wire does not affect the working of the total system.

The output of constant current source works from rated load to short circuit load. This feature is beneficial for the structural component's position control. Since the temperature of the shape memory alloy wire is proportional to the square of the current through it, it is possible to build a relationship between current and temperature. This helps in the design of the controllers, which is discussed later.

4. SYSTEM DESIGN

The block diagram of the system configured for shape memory alloy actuated structure is shown in Figure 4. There are three major building blocks other than structural component. They are programmable power source, control electronics and position feedback unit.

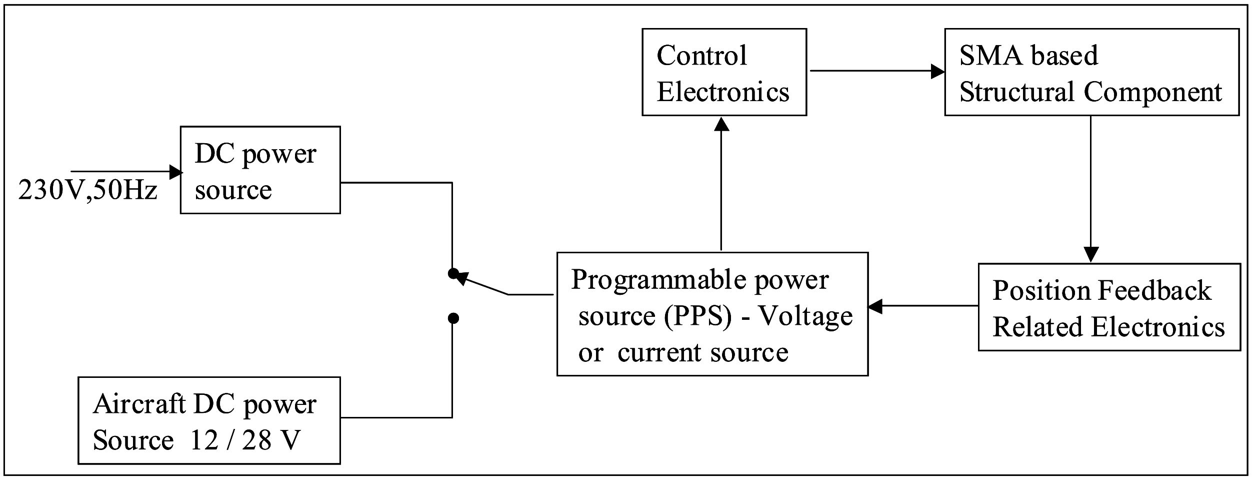
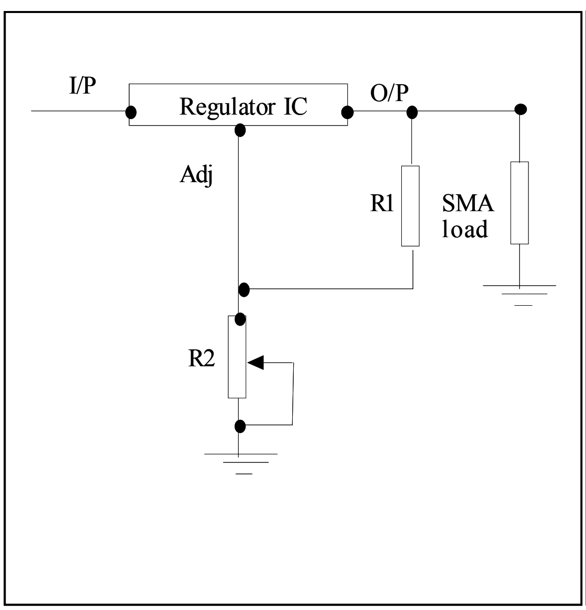


Figure 4. System configuration for SMA based actuation

The programmable power source is either constant voltage source or constant current source. Shape memory alloy wire of suitable diameter and length was chosen for the structural component. The constant voltage source is simple in design and suitable for open loop operation and also when the shape memory alloy load is located very near to the power source. On the other hand a constant current source is complex in design but seems to be the right choice for closed loop remotely (about 5 meter away) located load. Figure 5(a) shows the constant voltage source developed and Figure 5(b) shows the same with programmable feature. Figure 6(a) shows the constant current source developed and Figure 6(b) shows the same with programmable feature.



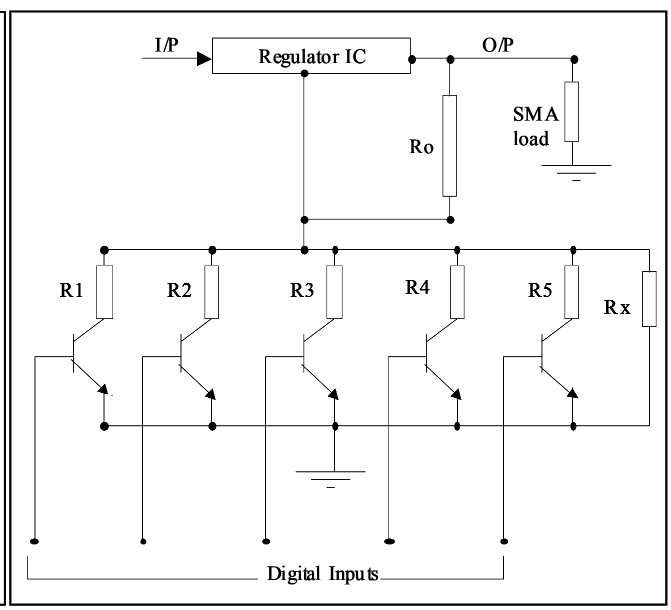
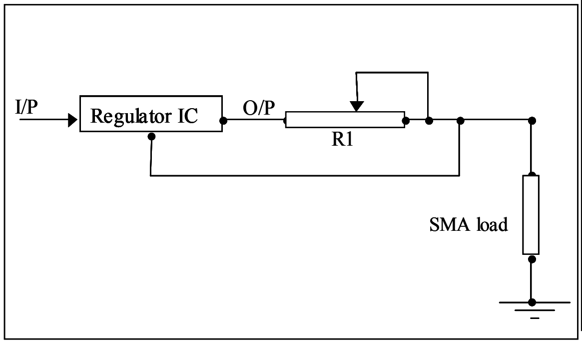


Figure 5(a). Miniature voltage source for SMA actuator. **Figure 5(b).** Programmable miniature voltage source for SMA actuator



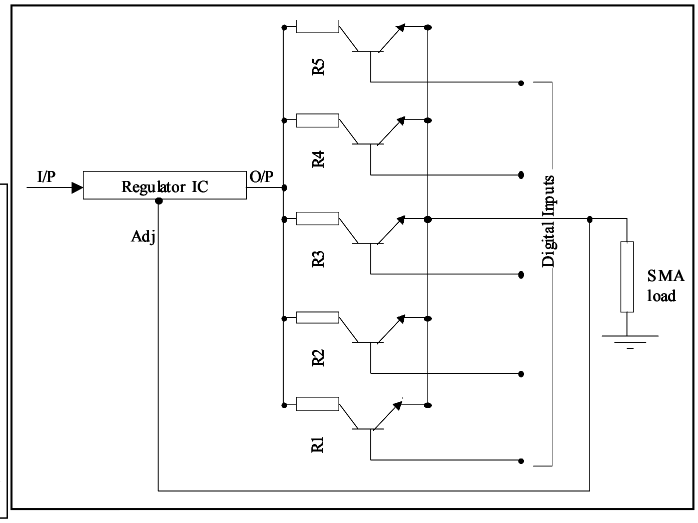


Figure 6(a). Miniature current source for SMA actuator. **Figure 6(b).** Programmable miniature current source for SMA actuator

The control electronics element working as interface between the power source and shape memory alloy load consists of switching devices and timers required to energise the shape memory alloy for the stipulated time during heat cycle and switch off the current to the shape memory alloy load during cool cycle.

The position feedback unit consists of a potentiometer and related electronics, which provides a voltage output proportional to the angular position (due to angular movement) of the structural component. For every angular position the position sensor provides the corresponding voltage. This voltage is compared with the set voltage (command voltage), which represents the desired position of the structural component in an error amplifier and fed back as an error signal to the power source to change its voltage there by changing the current flowing in the shape memory alloy wire to drive the component towards the desired position. The scheme developed for actuation of a typical structural component such as rudder of the aircraft is shown in Figure 7.

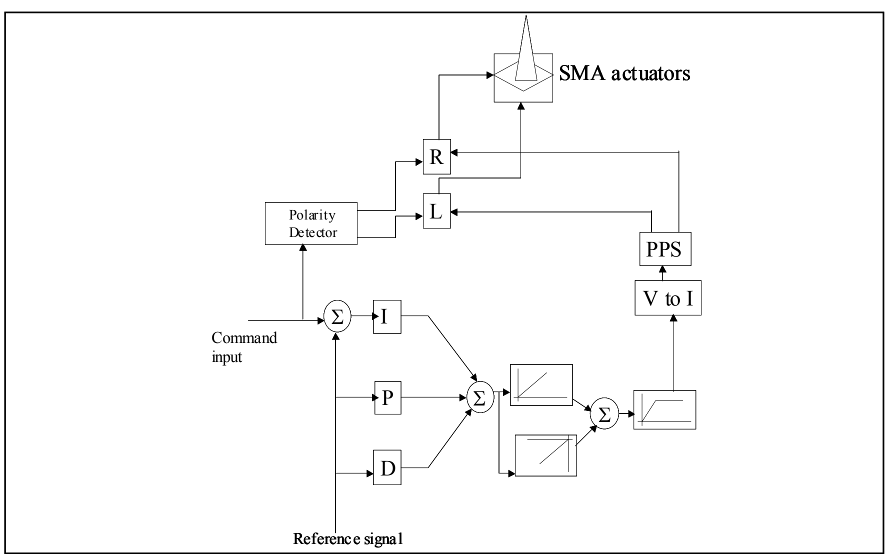


Figure 7. PID controller for SMA actuator

The scheme shows a proportional integral derivative (PID) controller implemented to impart desired movement and position a SMA based structural component. In this scheme the signal processing is carried out in the analog domain without resorting to computer (digital). Analog signal processing (ASP) involves calculation of system parameters such as gain, time constants and component values to ensure stable operation and reliability. Operational amplifiers are the basic building elements of the ASP design. Design with ASP involves two steps i.e choosing the basic type of operation and formulation of parameters.

The PID scheme basically consisting of proportional (gain), integral (integrator) and derivative (differentiator) blocks, works in the following way[3]. The command input is dependent on the desired angular position of the structural component and given in terms of volts. Actual position of the structural component is obtained from the position feedback element also in terms of volts. Let the position of the structural component be x1 degrees and the desired angle (position) is x2 degrees. Let V1 and V2 be the voltages corresponding to x1 and x2 degrees. Then the difference between V1and V2 will give the error voltage value. This error signal is generated using an operational amplifier. The error signal is fed to **I** stage of the **PID** controller, where as the feedback signal is given to the **PD** stage. Since the feedback signal determines the magnitude of the control action it is referred to as control signal.

In the structural component considered, SMA wires are mounted on both (left & right) sides of the structure .In this arrangement, the SMA is biased against itself i.e. when the right side SMA's are energised (strained) for a specific period of time (on time) the other half namely left side SMA's are not energised (not strained, off time) but still facilitate the right side movement of the structural component, from its neutral or zero angle position to its final angular position. In the next half of the cycle, right side SMA's are switched off or de-energised and left side SMA's are energised (switched on). The structural component moves towards its final left position and reaches it. This way the structural component does repeatable movements

The response of the structural component possesses symmetry for right and left side angle control from its mean (center) position. It implies the control action should be made independent of polarity. This is achieved using suitable electronics circuitry.

Figure (8) shows the circuit configuration designed and developed for implementing s PID controller.

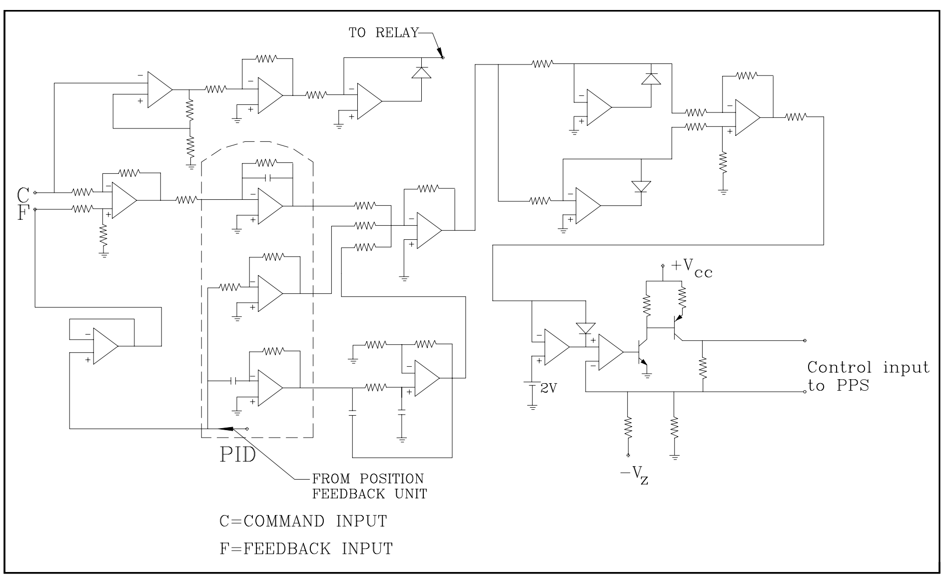


Figure 8. Circuit diagram of the PID controller

The output of the control unit is fed to a programmable power supply, which in turn controls the movement and position of the structural component. The relationship here is that the position of the structural component is dependent on the current passing through the shape memory alloy wire, which is in turn is controlled by the PID controller.

6. CONCLUSIONS

Some of the issues as related to behavior of shape memory alloy as an electrical load have been brought out. The constant voltage as well as constant current actuation of shape memory alloy has been discussed. The design of power sources and their integration into the system configured for actuating an actual structural component have been explained. A PID controller scheme to actuate and fine position the aerospace structural component has been configured and designed. Future work in this direction suggests that there is a need to develop miniature adaptive controllers using digital techniques.

7. ACKNOWLEDGEMENTS

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